UCRL-51164

POTENTIAL EXPOSURES FROM LOW-YIELD FREE AIR BURSTS

J. B. Knox, T. V. Crawford, and W. K. Crandall

December 26, 1971

Prepared for U.S. Atomic Energy Commission under contract No. W-7405-Eng-48

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Abstract

That there is little fallout hazard close to ground zero from free air bursts of tactical nuclear weapons may be true as long as wet deposition is excluded. However, in real operational situations one may not have the option of excluding wet deposition by selecting appropriate meteorology. Hence it is important to assess the consequences of wet deposition of the airborne radioactive inventory from such detonations. In this report we examine the potential close-in whole-body exposure from external gamma radiation and the thyroid exposure through the forage-cow-milk pathway for hypothetical 1, 10, and 100 kt all-fission air bursts. Our results indicate that complete scavenging of the 1-kt cloud, scavenging of the lower 10% of the 10-kt cloud, or scavenging of the lower 1-2% of the 100-kt cloud will give infinite external gamma exposure of a few hundred to 1000 rems 100 km downwind. If wet deposition should occur 1000 km downwind without any previous precipitation scavenging, the potential external gamma exposure is of the order of 1 rem. The results also indicate large potential thyroid exposures to man by way of the forage-cow-milk pathway from wet deposition of radioiodine (^{131}I).

Introduction

The hazard of close-in exposure from low-yield free air bursts has generally been considered negligible because no particles of sufficient size to fall out are generated in such bursts. This consideration may well be true as long as wet deposition is excluded. However, in real operational situations involving nuclear weapons one may not have the option of excluding wet deposition through the selection of meteorology. It becomes necessary, therefore, to quantitatively assess the consequences of wet deposition of the inventory aloft during the first 24 hr after such a detonation. The potential problem has been mentioned qualitatively but not assessed.[1]

Given the dimensions, radioactive loading, surrounding meteorological conditions, and rate of diffusion of a nuclear debris cloud, one can determine what the exposure rate at the ground surface at any time would be if a vertical column of radioactivity through the center of the cloud were brought to the surface. For the purposes of this paper, this vertical column (hereafter referred to as the "vertical integral") or a fraction of it (depending on how completely the precipitation system overlaps the debris cloud) is assumed to be brought to the surface by a precipitation scavenging mechanism.

We have evaluated the potential whole-body exposure from external gamma radiation and the thyroid exposures (through the forage-cow-milk pathway) from ^{131}I due to wet deposition from hypothetical 1, 10, and 100 kt all-fission free air bursts near the surface but with the fireball not touching the ground. We did this by calculating the changes in radioactive concentrations of the various clouds as a function of time and then converting these values to the desired quantities.

After a cloud has been defined in terms of dimensions and height of rise, it is allowed to mix with the atmosphere, thereby decreasing the concentration of radioactivity at any point within the cloud as a function of time. A knowledge of the initial distribution of the radioactive loading of the cloud, the initial size of the cloud, the rate at which the cloud diffuses, and the radioactive decay with time allows one to calculate the concentration of radioactivity at any point in the cloud at any time after stabilization. This permits a calculation of the rate of exposure should a vertical column of radioactivity of unit area within the cloud be brought to the surface and deposited over the same area. In these calculations we assume that the column of radioactivity—the vertical integral—is brought to the ground through scavenging by a precipitating system, a process referred to as wet deposition.

Once we assign the vertical integral a value based on the concentration of radioactivity within a cloud at a given time, we use appropriate conversion factors to obtain the corresponding exposure and exposure rate values. In these calculations the wet-deposited vertical integral is converted to (1) an exposure rate (at time of arrival) due to external gamma radiation, (2) an infinite whole-body exposure (from time of arrival) due to external gamma radiation, and (3) an exposure to a child's thyroid due to the passage of ^{131}I through the forage-cow-milk pathway. Infinite exposure due to gamma radiation from all sources (gross gamma) is calculated using the assumptions that no shielding occurs, that once deposition occurs it is not removed by weathering processes (e.g., erosion or runoff), and that the recipient of the exposure remains at the exposure location from the time of arrival to infinity. The ^{131}I values are determined by assuming that 25% of the deposited activity remains on the grass (75% is washed to the soil) to be immediately available for eating by the cow and hence the milk pathway to a child's thyroid.

Input Parameters

Table 1 gives the important input parameters for the calculations. The cloud center heights, thicknesses, and radii are taken from Ref. 2; the radiochemistry was provided by Tewes[3]; and the mean winds for

Table 1. Input cloud parameters for exposure calculations.

Yield (kt)	Center height (m)	Thick-ness[a] (m)	Radius[a] (m)	Gross[b] fission (pCi)	^{131}I (pCi)	Wind speed (km/hr)	Atmospheric dissipation, ε (ergs/g-sec) Slow diffusion	Fast diffusion	Vertical diffusivity (cm^2/sec) Slow diffusion	Fast diffusion
1	2,840	1760	920	4.44×10^{20}	1.4×10^{17}	39.6	0.5	3	1000	10,000
10	7,000	3060	2400	4.44×10^{21}	1.4×10^{18}	70.2	1	5	1000	10,000
100	11,700	5340	6000	4.44×10^{22}	1.4×10^{19}	72.0	0.7	3.5	1000	10,000

[a]Corresponds to two standard deviations from cloud-center concentration.
[b]After H+1 hr.

middle-latitude summer conditions are from Crutcher.[4]

Experience has shown that the value of the vertical integral after a few hours' travel time depends strongly on the amount of horizontal diffusion. This, in turn, is determined by the value of the atmospheric dissipation, ε (in ergs/g-sec), which may be calculated with reasonable accuracy from

$$\varepsilon = \frac{300}{z}\left(\frac{u}{5}\right)^3, \qquad (1)$$

where z is the level (in meters) at which ε is desired—i.e., z is the cloud center height above ground—and u is the wind speed (in m/sec) at that level.[5,6] Because of the strong dependence of the vertical integral on ε, diffusion calculations for each cloud are made using two values of ε, one higher and one lower than that given by Eq. 1. Corresponding to each value of ε is a value of the vertical diffusivity, which is relatively high or low depending on ε. The vertical diffusivity determines how fast the cloud diffuses upward and downward and has no bearing on the total value of the vertical integral. Values of ε given by Eq. 1 agree within a factor of 3 with climatological values calculated by Ellsaesser.[7]

Calculational Techniques

With the preceding data as input, we do the diffusion calculations using the Lagrangian diffusion code 2BPUFF (Ref. 5). This code was developed to calculate the dispersion of nuclear debris clouds created as a result of Plowshare cratering shots. It has been tested against five independent case studies (three Plowshare shots and two tests of reactor-propelled rocket engines) and has proved accurate to within a factor of 2 or 3 when compared with measured cloud-center and ground-level concentrations and deposition.[8-15]

The code treats the diffusion of a cylindrical cloud whose center height, thickness, radius, and radioactive loading are known at some initial time. The radioactivity is assumed to be distributed initially as a Gaussian curve; the physical dimensions of the cloud correspond to the two-standard-deviation ordinate of radioactivity. In the horizontal direction the cloud is assumed for all time to remain cylindrical with a Gaussian distribution of radioactivity. The horizontal dimensions of the cloud change with time and are a function of the input diffusion parameters and the initial cloud size. Hence, the cloud changes from a relatively small cylindrical volume of highly concentrated activity to a disk with a very large radius and a low concentration of activity. The vertical distribution of activity departs from the initial Gaussian shape because the vertical diffusivity varies with height and time and because deposition on the earth's surface occurs (due to turbulent impaction processes, not gravitational settling).

As the cloud diffuses, the code computes the value of the vertical integral through cloud center for a unit radioactive input, as a function of time and distance downwind. This is then transformed to radioactive concentration per unit area (in pCi/m^2) by combining it with the actual initial radioactive loading of the cloud and the radioactive decay over the travel time.

Thus, we obtain values of potential surface concentration (in pCi/m^2 at time of arrival), which enable us to determine what the consequences are of wet deposition of the entire vertical integral at some distance downwind.

To make this determination we convert the radioactive surface concentrations to a gamma-radiation exposure rate 3 ft above the ground by assuming an infinite plane and no shielding and by using the mean gamma energy for the nuclide (or, in this case, mixed fission products) involved. Infinite exposure is calculated by integrating the time-of-arrival exposure rate to infinity without permitting any weathering.

In doses through food pathways, the radionuclide surface concentrations are multiplied by factors that convert these surface concentrations to a dose to a particular organ through a particular food pathway.[16-19] The limiting food pathway in the United States for deposition of "fresh" debris is the forage-cow-milk pathway iodine dose to the child's thyroid. Therefore, for the purpose of this report we have considered only this pathway and have specifically considered only ^{131}I, the most important, but not the only, iodine isotope for this pathway. The conversion constant for this pathway has tacitly included assumptions about dairy practices (i.e., feeding in pastures, not on stored feed), milk production, milk consumption, etc. Hence, the pathway conversion constant can change considerably from location to location and season to season (pastures vs stored feed). The thyroid exposure can be eliminated, of course, by stopping the consumption of contaminated milk. Therefore, the thyroid doses presented here are only for comparison with the external gamma doses and should be reconsidered for specific situations.

Results

The 2BPUFF calculations, with the preceding data as input, indicate that deposition of the entire vertical integral would lead to infinite whole-body exposures due to external gamma radiation of roughly 1000 rems at distances up to nearly 100 km from ground zero for the 1-kt cloud, greater than 10,000 rems for the 10-kt cloud, and about 30,000 rems for the 100-kt cloud. At a distance of 1000 km these exposures are about 1 rem for the 1-kt cloud, 20-30 rems for the 10-kt cloud, and 200-300 rems for the 100-kt cloud. Figure 1 shows these results in graphical form.

The unequal separation of the three groups of curves is due primarily to the different travel speeds of the clouds: e.g., the 10-kt cloud is 100 km downstream in 1.2 hr vs 2.8 hr for the 1-kt cloud. Thus, although the 10-kt cloud has 10 times as much radioactivity and 12 times the volume, it has less than half the time to decay and diffuse before reaching a given point downstream.

Figure 2 gives the initial rate of exposure due to gross gamma radiation should the vertical integral be deposited at a given distance from ground zero. The initial exposure rate at 100 km due to the 1-kt burst with slow diffusion is about 100 R/hr, for 10 kt about 2000 R/hr, and for 100 kt nearly 6000 R/hr.

Figure 3 presents the infinite exposure to a child's thyroid due to the passage of ^{131}I through the forage-cow-milk pathway. In the 2BPUFF calculations, the vertical integral is converted to a ^{131}I yield in pCi/m^2. To convert this to exposure to a child's thyroid we have used a conversion constant of 1.0×10^{-5} $R/pCi/m^2$. Values of this constant range from 3.5×10^{-6} (Ref. 20) to 3.3×10^{-5} (Ref. 18).

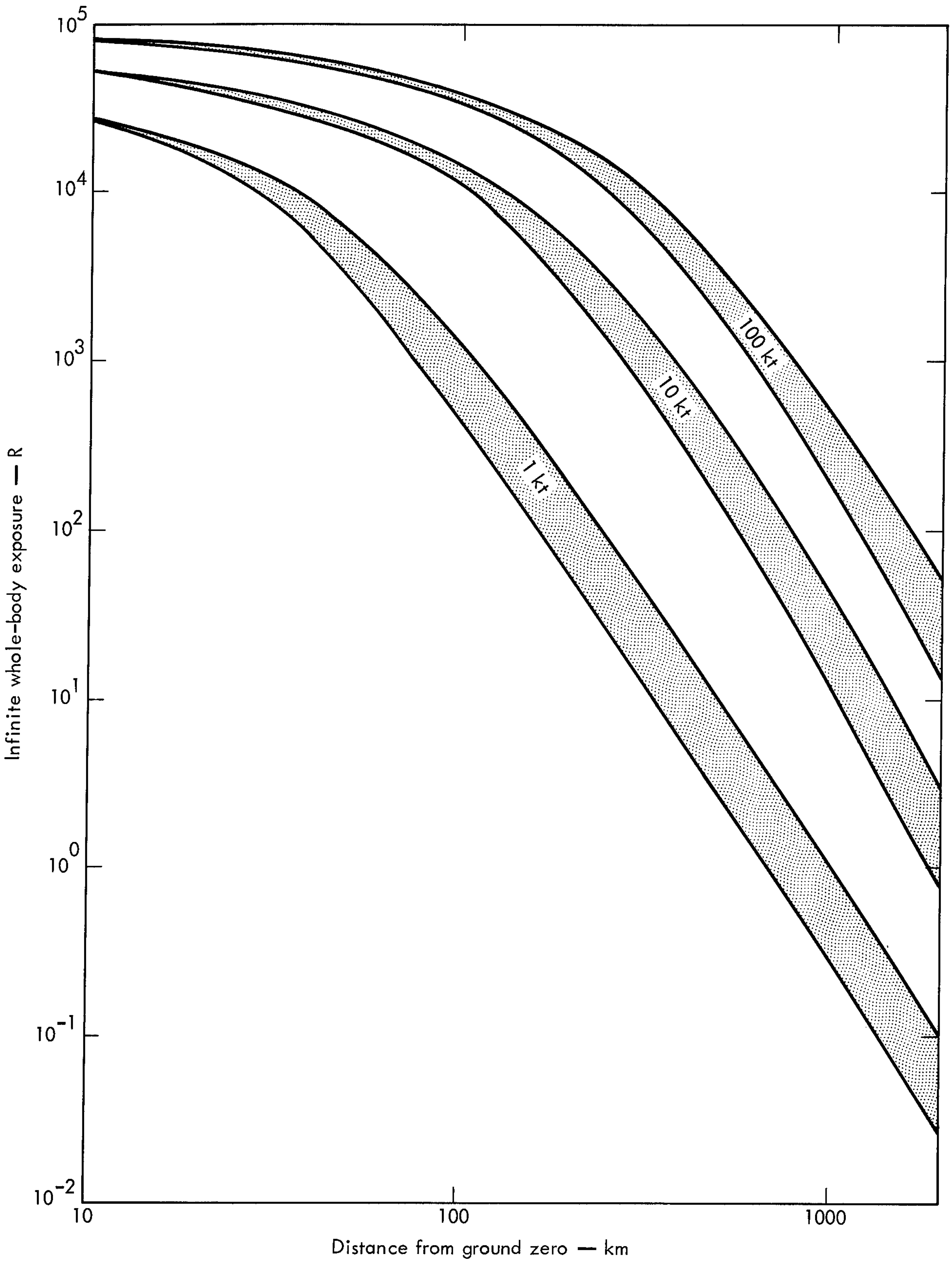

Fig. 1. Vertical integral (infinite whole-body exposure) due to gross gamma radiation as a function of distance from ground zero. The upper curve for each yield represents the case of slow horizontal diffusion; the lower curve represents the case of fast diffusion.

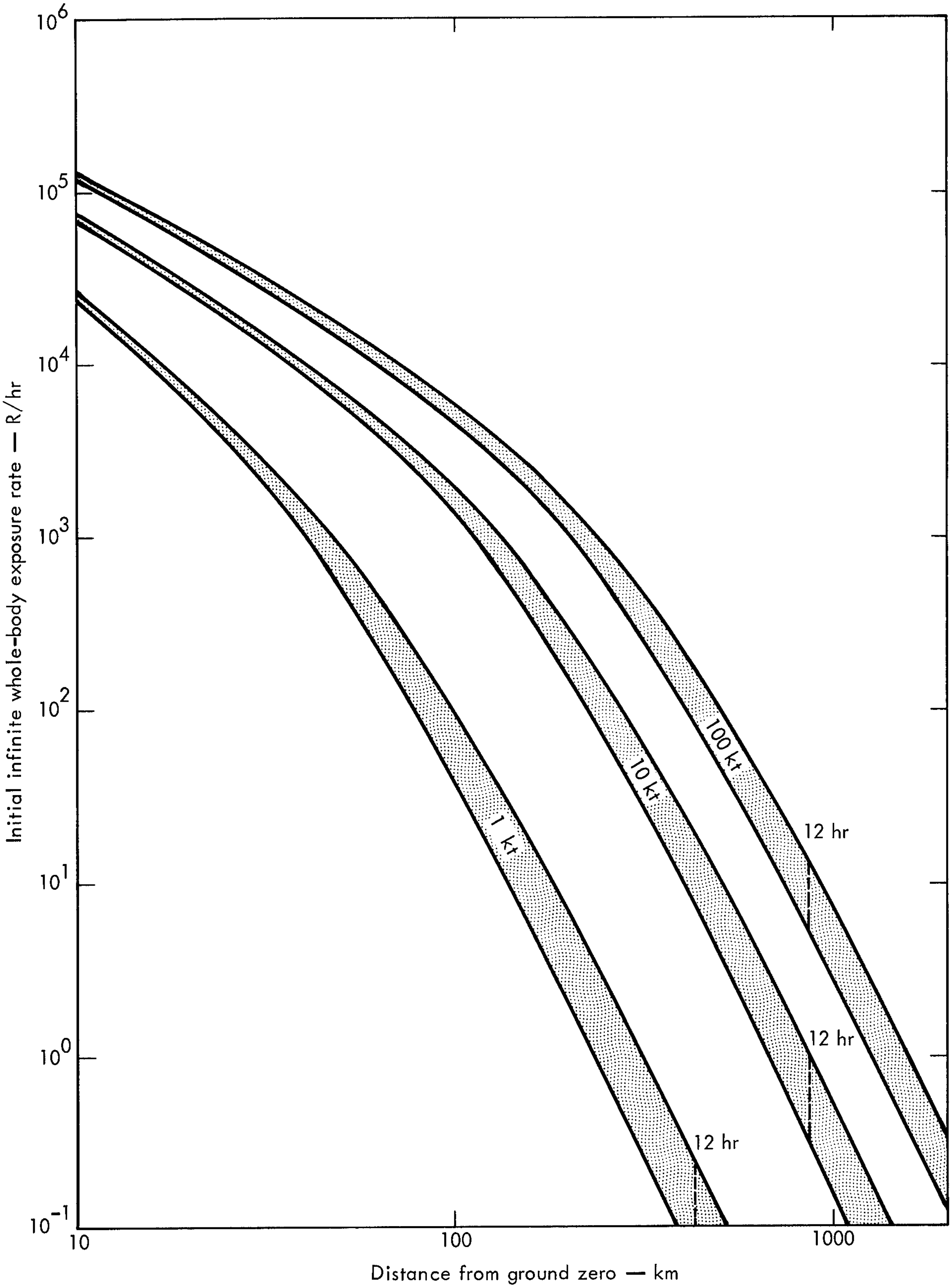

Fig. 2. Initial gamma exposure rate due to the deposition of the vertical integral at various distances from ground zero. The upper curve for each yield represents the case of slow horizontal diffusion; the lower curve represents the case of fast diffusion.

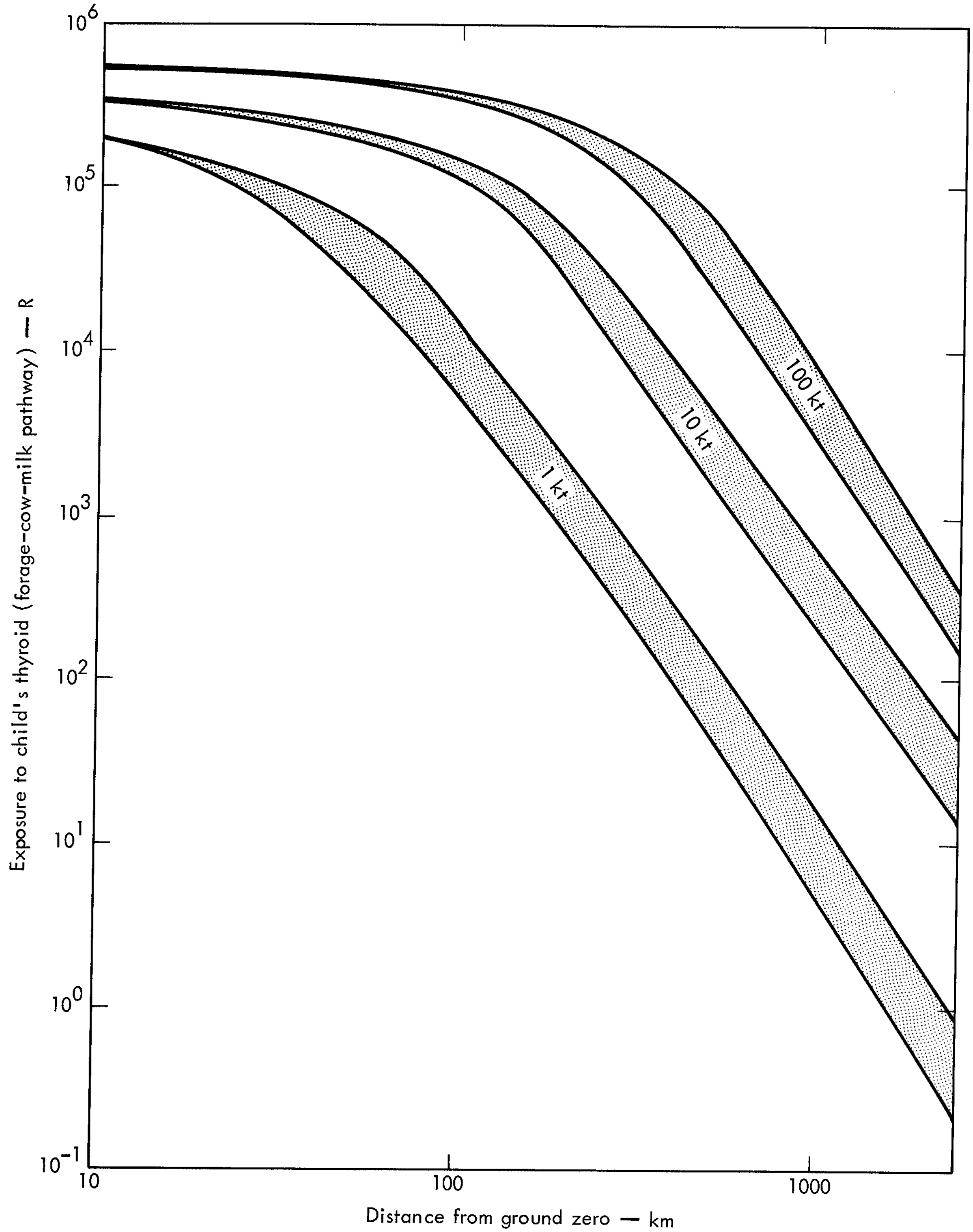

Fig. 3. Infinite gamma exposure to a child's thyroid due to the passage of ^{131}I through the forage-cow-milk pathway after deposition of the vertical integral at various distances from ground zero. The upper curve for each yield represents the case of slow horizontal diffusion; the lower curve represents the case of fast diffusion.

Interpretation of Results

SCAVENGING EFFICIENCY

For any of the above-mentioned exposures at the ground to be realized, the rain-producing clouds must be able to scavenge the nuclear cloud throughout its entire depth. In the case of the 1-kt cloud, a summer rainstorm could rather easily penetrate the entire depth during the first few hours after detonation. Assuming, then, that the precipitation mechanism has a 90-100% scavenging efficiency, it would not be unreasonable to expect full values of the vertical-integral exposures and exposure rates to occur at the surface as a result of a rain shower. The band of high contamination will be quite narrow, however, and in most cases highly intermittent. Once precipitation occurs, of course, material is no longer available for scavenging farther downwind. If a person were subjected to exposure in this manner his total exposure could be held to less than 100 rems (for the 1 kt event at 100 km) if he were removed from the area and decontaminated within 1 hr. If only one, or even a few, 1-kt devices were detonated simultaneously, an individual would be able to walk out of the contaminated area; but this would probably not be practical in the event of wet deposition from a large number of nearly simultaneous events.

Circumstances differ in the 10-kt and 100-kt cases. These clouds are much higher than the 1-kt cloud and a rainstorm is far less likely to penetrate to the upper levels of the debris clouds, particularly the 100-kt cloud. (Remember that we have limited the problem to the three cases studied and that these cases are based on established mean values for several parameters. Actual cases may not conform to these means; for example, cloud stabilization heights may be higher or lower than those used in this report.) Figure 4 shows the percent of the vertical integral below a given height in the atmosphere; it is valid essentially for the first 24 hr. After the exposure or exposure rate (corresponding to 100% of the vertical integral) is determined for a given distance downstream, the percent of that total that

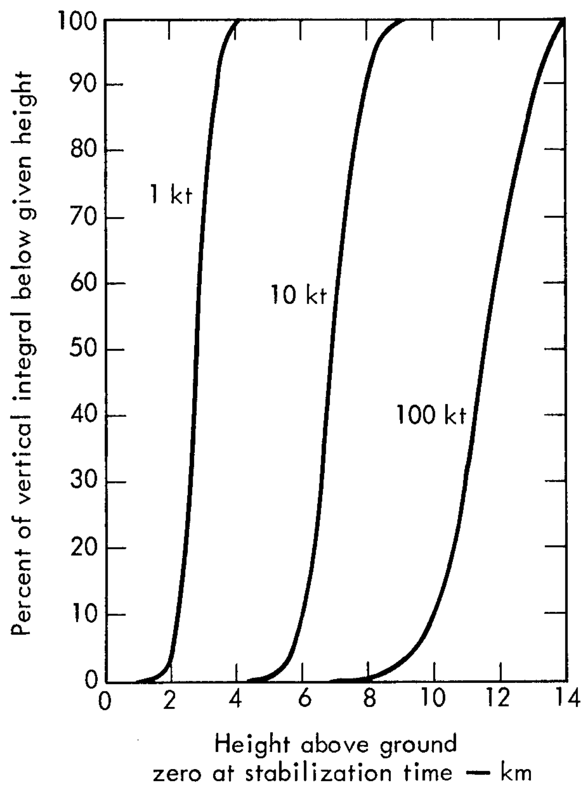

Fig. 4. Fraction of the vertical integral lying below a given height in the atmosphere. The vertical-integral exposure values at the stabilization time of the cloud are: 1-kt cloud, 27,000 R whole-body and 198,000 R ^{131}I to a child's thyroid; 10-kt cloud, 52,800 whole-body and 350,000 R ^{131}I; 100-kt cloud, 85,000 R whole-body and 557,000 R ^{131}I.

can be obtained by scavenging to a given height can be determined from this figure.

Figure 4 shows that a shower need only penetrate a short distance into a 10-kt cloud, say to 6 km, to scavenge about 10% of the available particulates and deposit enough on the surface to cause an exposure rate of about 175 R/hr 100 km downwind. For the 100-kt cloud, deposition of the cloud below 9 km (approximately 2% of the cloud) would give an exposure rate of 100 R/hr. Again, during the first few hours after the burst, rapid removal and decontamination would keep exposures low. However, scavenging to greater heights will provide correspondingly greater dose rates.

Table 2 summarizes the potential surface exposures and exposure rates for each of the three burst yields for three different downstream distances. The fact that only portions of the higher two clouds are scavenged is reflected in the figures. The data show that if any of the clouds rain out shortly after detonation prohibitively high doses occur at the surface. At 100 km downstream, gamma dose rates are such that rapid removal of exposed individuals would keep total exposures within tolerable limits, except in multiburst situations. Thyroid exposures remain extremely high at both 10 and 100 km. At 1000 km the dose rates become very small; times of the order of 100 hr would be required to approach the infinite doses indicated.

As has been mentioned before, the large exposures and exposure rates indicated at the close-in distances would occur over relatively small areas (tens of square kilometers) for a single detonation. The smaller values at the more distant points would prevail over relatively larger areas (hundreds or thousands of square kilometers). Much larger areas could be involved in the multidetonation situation, which needs to be investigated but is beyond the scope of this study.

The above calculations are based on the movement and diffusion of a contaminated (Gaussian distribution) cylindrical cloud that maintains its shape. Hence,

Table 2. Potential surface exposure and downstream exposure rates.

Yield (kt)	Fraction deposited (%)	Distance downwind (km)	Infinite whole-body external gamma dose (rem)	Exposure to child's thyroid due to forage-cow-milk pathway (rem)	External gamma exposure rate at time of arrival (R/hr)
1	100	10	25,000	200,000	25,000
		100	400-1200	5000-15,000	35-100
		1000	0.3-1.0	5-15	<0.01
10	10	10	5000	30,000	7000
		100	1000-1500	10,000-15,000	150-200
		1000	1-4	20-60	0.015-0.05
100	1	10	800	5500	1200
		100	300-350	3500	45-55
		1000	1.5-5	25-70	0.02-0.06

it may be argued that figures that purport to give the vertical integral through the cloud center should be unreasonably high, because no vertical wind shear is accounted for in the calculations. This argument is countered, however, by the fact that any showers penetrating the debris cloud will entrain contaminants from the rest of the cloud, which, we feel, would increase the concentration in about the same proportion that shear decreases the concentration.

GIBSON'S CALCULATIONS

Gibson <u>et al</u>., in a 1953 paper,[21] calculated total dose and dose rates from external gamma radiation due to the deposition of a debris cloud during stable rainfall conditions. Their assumptions included (1) the distribution of radioactivity within the cloud is uniform; (2) the cloud is transported at a constant velocity; (3) the cloud radius increases at a constant rate with time; (4) all radioactivity is scavenged by raindrops; (5) the time of fall of the raindrops depends on a prescribed function of the height above ground, and the dependence is linear over three separate height intervals (the mean velocity of fall varies between 13 ft/sec up to 9000 ft and less than 3 ft/sec at 21,000 ft; and (6) no rain is found above 21,000 ft in the summer and 16,000 ft in the winter (this assumption eliminates strong convective cells as scavenging mechanisms).

When we compare the total dose and dose rates from external gamma radiation due to wet deposition from the 1-kt cloud, as calculated by our method and Gibson's, the 2BPUFF results at a given distance are higher by 1-2 orders of magnitude. This difference is attributed to the following factors:

1) Gibson <u>et al</u>. used a conversion factor of 1230 R/hr for the dose rate due to 1 kt of fission products distributed over 1 mi^2. We used the more modern factor, 2600 R/hr, in the 2BPUFF calculation.

2) The 2BPUFF calculation assumes the worst conditions by calculating the vertical integral at the cloud center. Since the vertical integral is distributed horizontally as a Gaussian curve, the value at the center is a factor of 2 to 3 higher than the mean value over the horizontal area of the cloud.

3) The debris is distributed over a greater area in the Gibson method, since the scavenged debris in the Gibson model is deposited at a relatively modest speed of about 4 m/sec. This fact would account for a factor of 5 to 15.

The physical process associated with the distribution of debris in Gibson's model is a moving, large-scale storm with a light-to-moderate precipitation rate[22] in which a small debris cloud is embedded. The use of the vertical integral from 2BPUFF calculations to estimate potential wet deposition represents either (1) a slow-moving convective shower embedded in the debris cloud, with the precipitation rate in the convective shower moderately heavy but short lived, or (2) a fast-moving debris cloud passing through an orographically fixed rain shower. The type of precipitation visualized by Gibson <u>et al</u>. is more characteristic of winter situations, and that represented by the vertical integral for 2BPUFF is more characteristic of spring and summer precipitation or orographically induced precipitation.

DRY DEPOSITION

A second mechanism of deposition is by dry deposition processes. From a free air burst, which is high enough that the fireball does not touch the ground, fallout in the traditional sense is minimal. The only source of particles for fallout is from the device itself. There may be a radiation field under the burst point due to neutron activation of the soil.

Small particles (say, those less than 10 μ in diam*) are formed as a result of the air burst. These small particles are generally too small to fall, but they can diffuse downward and be deposited by atmospheric turbulence processes. 2BPUFF can treat this situation. The calculation depends on the calculated ground-level air concentrations and dry deposition, and it is quite sensitive to the initial activity distribution with height (ground level through cloud center) assumed in the initial cloud. In our review of available information to date, we have found little to guide us in this choice. Therefore, we are reluctant to present any firm calculations with 2BPUFF on dry deposition from a free air burst at close-in distances. Some general comments are in order, though:

1) For level ground, dry deposition will be greater for passage of a low cloud than for passage of a high cloud.

2) The presence or absence of an inversion layer between the cloud and the ground may make a difference of up to five or more orders of magnitude on the amount of dry deposition. The greatest dry deposition will occur under conditions of strong vertical mixing (no inversion), while the least deposition will occur with a strong inversion layer (stable conditions) between the cloud and the ground.

3) Higher ground will get greater doses and dose rates than lower ground.

VERIFYING THE FAST-RAINOUT ASSUMPTION

Experimental Evidence

As previously discussed, the authors in preparing this study have made a critical assumption that the portion of the vertical integral overlapped by a precipitating cloud system is quickly brought to the ground. It is pertinent to ask if there is experimental evidence to support this assumption and if different approaches to calculating rainout are consistent with this assumption.

With regard to experimental evidence, the amount of ^{90}Sr deposited in precipitation at Fargo, North Dakota, on July 16, 1957, was consistent with vertical-integral calculations[24] done for the Diablo Event at the Nevada Test Site on July 15. The calculations done with 2BPUFF for the Cabriolet Plowshare Event, which treated scavenging as a function of precipitation rate, time, and height of precipitation, showed that scavenging removed more than 90% of the vertical integral. This result compared well with the amount of radiation measured on the ground and in the cloud before and after the debris encountered the precipitation.[13,25]

These data strongly suggest that it is reasonable to expect precipitation scavenging to deposit the full vertical integral,

*As a rule, the particles have a diameter between 0.01 and about 20 μ, and refractories, like ^{95}Zr, are on particles less than 8 μ in diameter. About 90% of the ^{95}Zr is on particles at least 3 μ in diameter.[23]

although the U.S. has had no experience with this phenomenon at close-in ranges.

Calculational Evidence

It is also pertinent to test the consistency of this critical assumption against various calculational approaches for estimating wet deposition from rainout. Two approaches appear as reasonable bases for comparison: (1) observed rainout coefficients as determined by cosmogenic tracers[26] and (2) the observation by Engelmann[27] that the concentration of radioactivity in rainwater is 10^6 (by volume) times the air concentration in the clouds from which the rain was formed.

Considering the first approach, experimental work indicates that rainout coefficients are of the order of 10^{-3} sec^{-1} for rain rates of about 1 mm/hr (the relationship is approximately linear with rain rate), as measured in precipitation systems in western Washington. Thus, the fraction of the scavengable radioactivity remaining aloft in rainout is $\exp(-10^{-3} t)$, where t is in seconds, from which one can determine that 83% of the scavengable radioactivity is deposited in about 0.5 hr.

Engelmann[27] has suggested that the concentration of radioactivity in rainwater is 10^6 (by volume) times the concentration in the clouds from which the rain formed. Using this factor, the cloud center concentrations from 2BPUFF, and the Gaussian distribution of radioactivity within the cloud, we calculated the amount of rainfall necessary to deposit the entire vertical integral on the ground. Table 3 gives the rainfall amounts for each cloud at three downstream distances. These figures are consistent with those calculated

Table 3. Precipitation required to deposit the vertical integral on the ground.

Distance from ground zero	Amount of precipitation (cm) 1-kt cloud	10-kt cloud	100-kt cloud
10 km	0.18	0.32	0.53
100 km	0.18	0.33	0.53
1000 km	0.19	0.33	0.54

using rainout coefficients in that they show that the cloud can be depleted of a large percentage of its activity by relatively little rainfall. While the amount of precipitation required to deplete the cloud does not change much with distance, the amount of radioactivity precipitated does, as has been shown in Figs. 1-3.

Typical precipitation rates in middle-latitude showers can range from 10 to more than 50 mm/hr. Hence, using the results of Table 3, which are based on Engelmann's experimental result, we would conclude that the early precipitation from a shower cloud removes most of the scavengable debris in a few to 10-20 min.

On the basis of these experimental and calculational comparisons, we find a very reasonable consistency between the critical fast-rainout assumption and (1) limited U.S. experience with wet-deposition hot-spot documentation and (2) present theoretical approaches for estimating rainout.

LATERAL EXTENT

It is pertinent now to discuss the lateral extent of the gamma radiation fields produced by the interaction of scavenging systems and nuclear debris clouds. To this end, we offer the following general guidelines:

1) If the precipitation scavenging involves convection or cumulus cells, then the horizontal scale of the convection cells plays a dominant role in determining the lateral extent of the wet-deposition pattern.

2) If the scavenging system involves synoptic-scale weather systems, then the horizontal scale of the debris cloud is the controlling factor in determining the extent of the wet deposition pattern at early times and probably up to 12 hr.

3) For times of 12-24 hr, both the scale of the debris cloud and the scale of the scavenging system are important. In this event the lateral extent cannot exceed the scale of the debris cloud, but it could be smaller due to the lack of complete overlapping of the scavenging system and the debris cloud.

To quantify these general guidelines, we cite the following calculational and experimental information.

Figure 5 shows reasonable estimates of the radii of each of the three clouds as a function of time. A radius is determined as that distance along the horizontal through cloud center at which the in cloud concentration is 25% of the cloud center concentration (corresponding to about 1.66 standard deviations and containing slightly more than 90% of the total radioactivity). Note that the 1-kt cloud dominates in size 100 km downstream due to the longer travel time.

Byers[20] and Semonin[28] have determined the sizes of precipitating systems—Byers in Ohio and Semonin in Illinois. Both found that a width of 4-8 km would characterize a majority of individual-cell precipitating systems of the size of concern in this report. At early times these widths would prevail in determining the width of the surface pattern. The speed of the clouds would determine the length of the pattern; typical rainout times are 20-40 min.

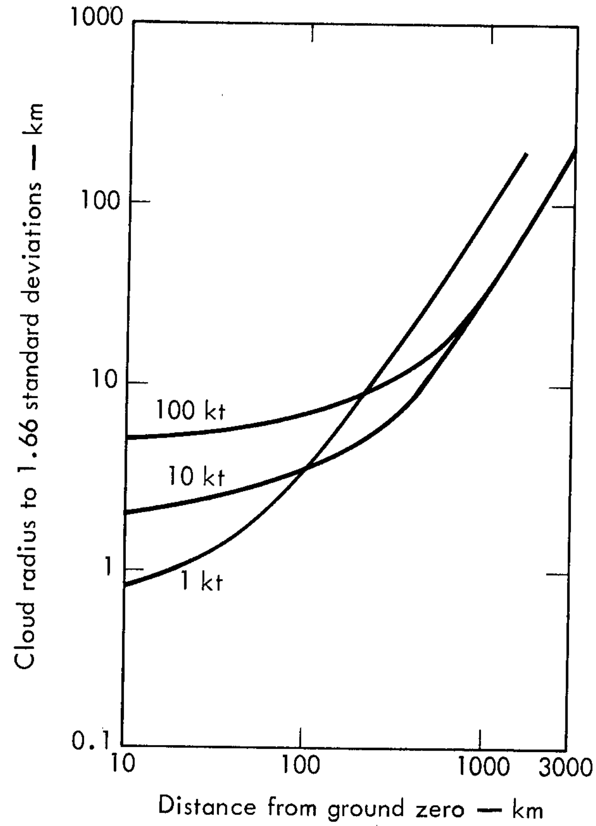

Fig. 5. Cloud radius as a function of distance downstream for the case of low atmospheric dissipation (ε). The radii may be 20-40% higher for high-ε cases.

At later times, the radioactive clouds will be much larger and would be subject to partial scavenging by isolated systems or to general scavenging by larger, organized systems. Surface patterns in the isolated case would be similar in size and shape to those described in the early-time case; i.e., 4-8 km wide and of the order of 5-20 km long. Scavenging at later times by larger, organized systems would result in complex arrangements of hot spots over an area comparable in size to that of the nuclear cloud. Lateral widths in this case would be indefinite due to the possibility of overlapping rainout patterns. Individual cell patterns would still be of the size already described, however.

Although the distribution of radioactivity within the cloud is Gaussian in form, it does not necessarily follow that the lateral distribution of exposure or exposure rate at the surface from a given precipitation cell will be thus distributed within the pattern. The turbulent mixing within the system may well serve to create off-center hot spots or may spread the radioactivity rather evenly over a given area. Other things being equal, however, the larger the area over which the radioactivity is spread the smaller the value of the mean exposure or exposure rate over the area as a whole.

Figures 6 and 7, taken from Semonin,[28] illustrate the concentration of lithium deposited over an area of Illinois from a seeded cloud system (Fig. 6) and the total rainfall amounts for the lithium-treated storm (Fig. 7). The hot spots do not correspond to the areas of maximum rainfall. Figure 8 shows the rainfall rates during a 4-min period from various cells within an organized system. The larger patterns have widths of 5-7 km. (The tops of the storms represented in these figures are estimated to be between 30,000 and 40,000 ft.)

However fragmentary these field data may appear, the findings support the

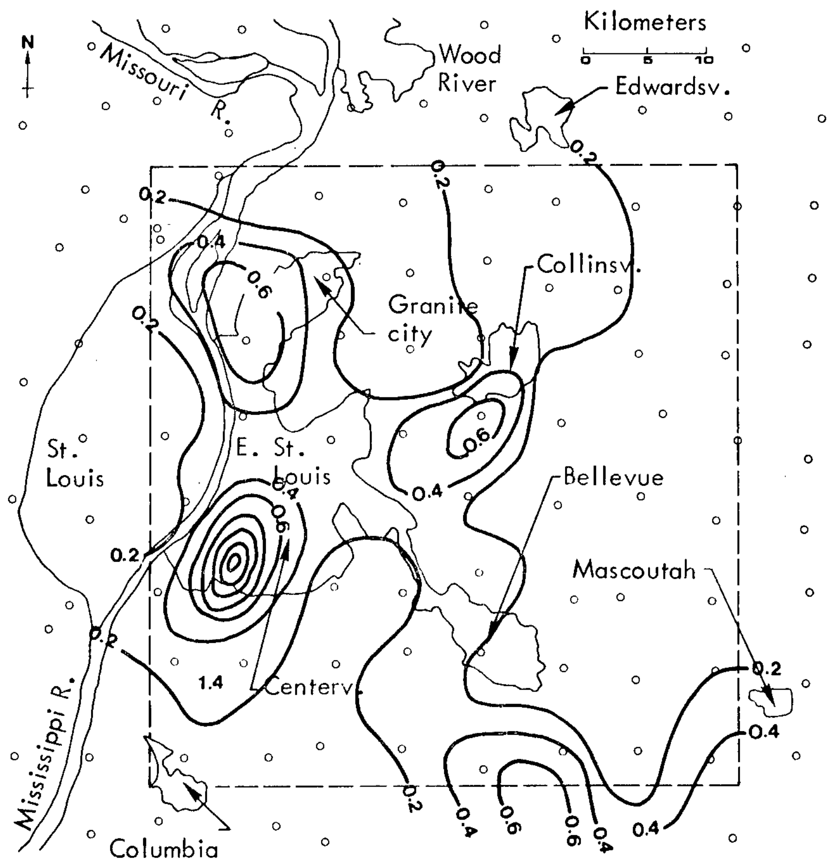

Fig. 6. Lithium concentration (ppb) in seeded cloud system over E. St. Louis, Ill., area on Aug. 14, 1971 (after Semonin[28]). Dots are recording points.

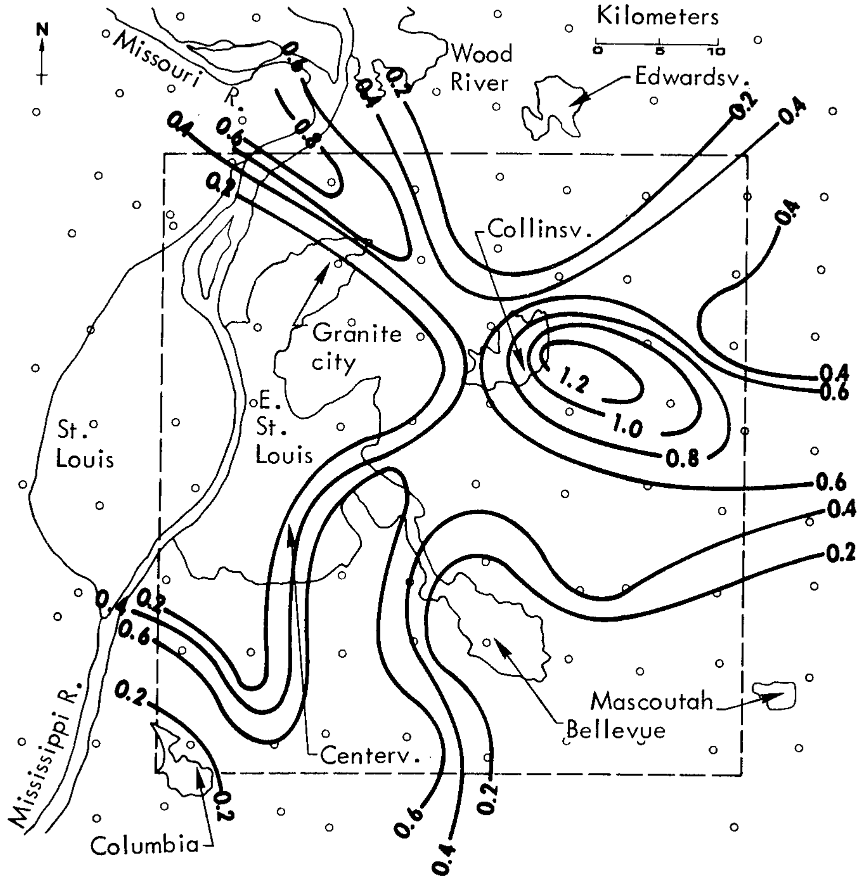

Fig. 7. Total rainfall (in.) for lithium-treated storm over E. St. Louis, Ill., area on Aug. 14, 1971 (after Semonin[28]).

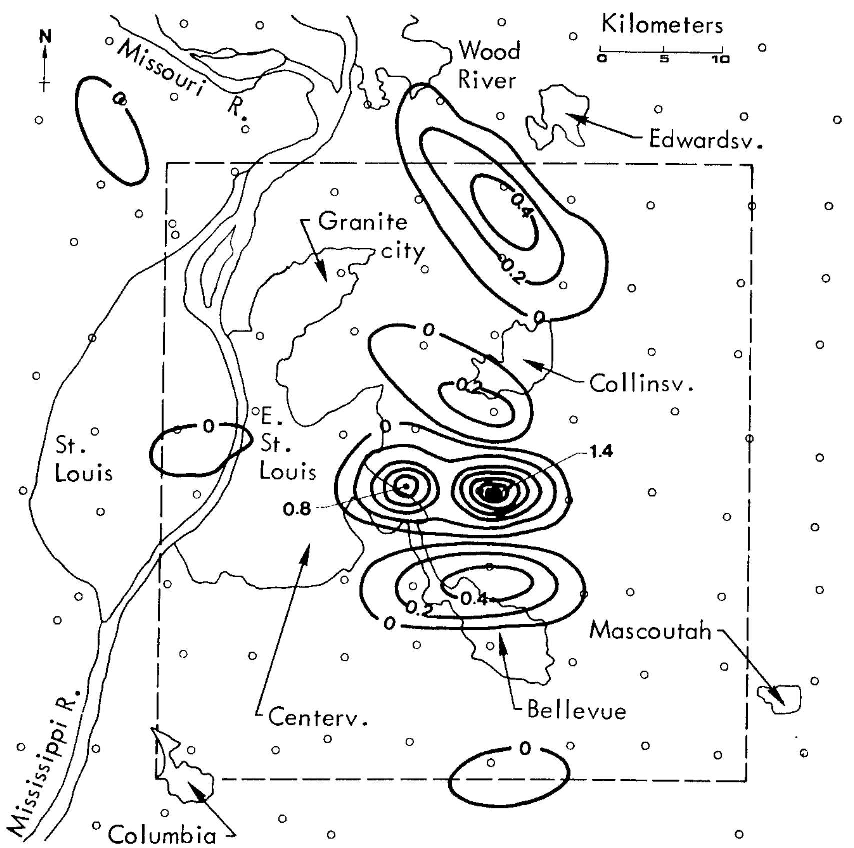

Fig. 8. Average rainfall rate (in./hr) over a 4-min period on June 18, 1971, for the time ending 1340 CDT (after Semonin[28]).

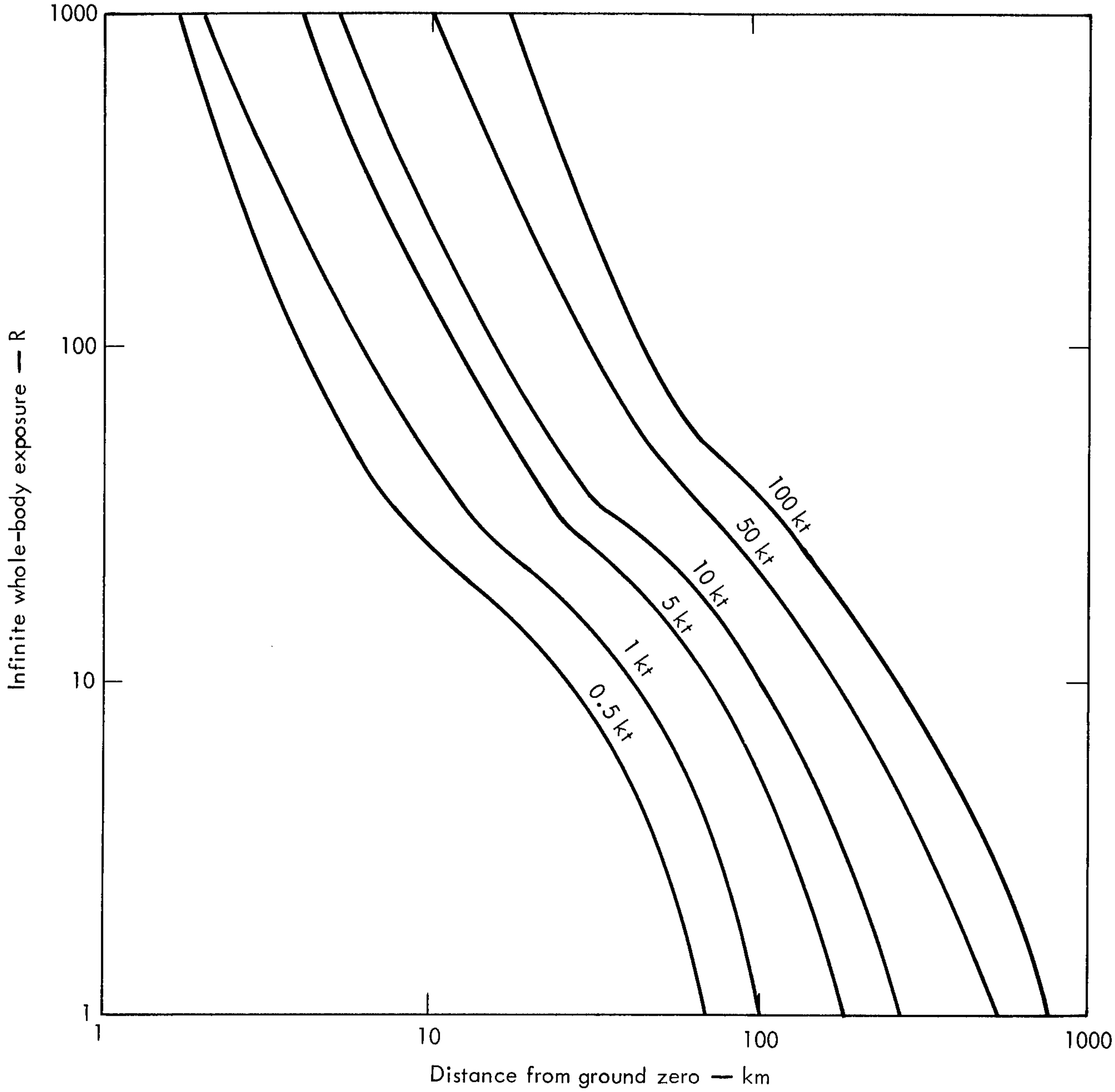

Fig. 9. Infinite whole-body exposure due to dry fallout from all-fission surface bursts of various magnitudes as a function of distance downstream.

above guidelines with respect to the correspondence of the deposition pattern with the scale of the convective cell.

COMPARISON OF WET DEPOSITION FROM FREE AIR BURSTS WITH DRY FALLOUT FROM SURFACE BURSTS

Table 4 compares the infinite whole-body exposure from external gamma radiation for wet deposition from free air bursts of all-fission nuclear devices with that for dry fallout from surface bursts. Figure 9 illustrates the dry fallout data. The tables show the results for two ranges—10 and 100 km. In the wet-deposition case we have assumed that there has been no previous scavenging of debris

Table 4. Comparison of the exposure due to wet deposition of free-air-burst debris with that due to dry fallout from a surface burst for two downstream ranges. Both bursts are all-fission nuclear detonations.

	Infinite whole-body external gamma dose (R) due to wet deposition of free air burst		Infinite whole-body dose (R) due to dry fallout of surface burst	
Yield (kt)	10 km downstream	100 km downstream	10 km downstream	100 km downstream
1	25,000	400-1200	45	1
10	5,000	1000-1500	240	10
50	~1,500[a]	~400[a]	950	20
100	800	140-200	~3000	35

[a]Interpolated.

prior to its arrival at the range of deposition (10-100 km).

The most important conclusion to be drawn from these estimates is that the risk of high individual exposures is much greater for a tactical nuclear war in the free-air-burst mode with wet deposition than for a tactical war in the surface-burst mode with no wet deposition processes. The physical reason for this is that for wet deposition of a free air burst more of the produced radioactive inventory is deposited in a smaller area than for the dry fallout from a surface burst. To a first approximation, the man-rem exposures from both forms of tactical war are similar, assuming uniform population distribution.

Future Work

Numerous questions and uncertainties have arisen as a result of this work. Additional studies should be done in the following areas:

1) Climatological data concerning the rainout mechanism for areas of interest. Information such as depth of convection, cell size, the fraction of the time that rainbearing systems are present, the type of flow above rainbearing systems, and the amount of precipitation to be expected from rainbearing systems should be determined for these areas.

2) A multiburst wet-deposition pattern for areas of interest. This would provide typical wet-deposition patterns for these areas based on various typical meteorological conditions that support convective activity.

3) A numerical simulation model for studying the problem of injection of debris into a convection cell. The purpose of the model would be to enable one to estimate the fraction of the vertical integral scavengable by natural convective systems.

4) An assessment of the potential surface contamination due to dry deposition from a free air burst. This would make possible a comparison of calculated exposures with data from past U.S. experience.

5) The effect of multivortex initial conditions on the height of rise. This effect is developed by Fohl,[29] who suggests that the height of rise of two buoyant fireballs, released simultaneously and in close proximity, will be decreased due to mutual interaction.

6) An accurate determination of the particle-size distribution from a free air burst. Data from several past nuclear events could be developed for different yields, and existing theory could be extended where pertinent and tractable.

7) Investigation of the effect of vertical wind shear on the value of the vertical integral. This evaluation needs to be included in future assessments of potential exposures from tactical nuclear weapons.

If one had the results of the above studies, one could more realistically and confidently describe the wet deposition problem associated with the tactical uses of nuclear weapons.

Acknowledgments

The authors wish to acknowledge the interest of Dr. Harry Reynolds in the question of exploring the potential effects of wet deposition in the tactical uses of nuclear weapons, and the constructive comments made by Dr. R. J. Engelmann, AEC Division of Biology and Medicine, during the course of the study.

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